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In-Plume Emission Test Stand 2: Emission Factors for 10- to 100-kW U.S. Military Generators

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ABSTRACT

Although emissions of air pollutants from some military tactical equipment are not subject to the emissions standards, local communities near military bases must conform to the National Ambient Air Quality Standards. Military diesel generators are widely used in training. A portable in-plume system was used to measure fuel-based emission factors (EFs) for particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HCs) for 30-, 60-, and 100-kW generators at five load levels and for cold starts. It was found that EFs depend on multiple parameters including engine size, engine load, unit age, and total running hours. The average CO EF of generators tested was 5% lower, and the average NO_x EF was 63% lower than AP-42 estimates; average PM EF was 80% less than the AP-42 estimates. A 2002 model-year 60-kW engine produced 25% less PM than a 1995 engine of the same family with similar running hours. CO EFs decrease with increasing engine load, NO_x EFs increase up to mid-loads and decrease slightly at high loads, PM EFs increase with loads for 30- and 60-kW engines. CO and PM have higher EFs and NO_x has a lower EF during cold starts than during hot-stabilized operation. PM chemical source profiles were also examined.

INTRODUCTION

Emissions of regulated air pollutants from military training operations influence the ability of communities to meet federal and state air quality regulations. Although tactical military vehicles may be granted a national security exemption from exhaust emission standards and diesel fuel standards,[1] communities located near military bases must still conform with National Ambient Air Quality Standards (NAAQS) and other regulations. Air quality in the vicinity of military training facilities may be affected by exhaust from diesel generators and nonroad vehicles. Generators are widely used in military training to provide electricity to weapon systems, communications, and aviation ground support.

Diesel engines emit nitrogen oxides (NO_x), hydrocarbons (HCs), carbon monoxide (CO), particulate matter (PM), and other pollutants.[2] Diesel particulate matter (DPM) is a complex mixture of partially oxygenated fuel and engine oil and falls almost entirely into the size range of PM less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$). DPM is primarily composed of elemental carbon (EC) and organic carbon (OC), including polycyclic aromatic hydrocarbons (PAHs)[3] and is identified by the California Air Resources Board (CARB) as a toxic air contaminant.[4] Components of PM emissions, such as PAHs, have been identified as toxic and carcinogenic with potential adverse health effects.[5,6] Available evidence indicates that there are human health hazards from exposure to diesel exhaust[7]; engine emissions have been associated with increased cases of lung cancer and noncancer health effects that impair respiratory function.[8] Nationwide, emissions from nonroad diesel engines account for 44% of total DPM and 12% of total NO_x emissions from mobile sources.[9] Until the mid-1990s, emissions from nonroad diesel sources were largely uncontrolled in the United States. Most nonroad diesel engines were exempt from fuel formulation (e.g., sulfur content) requirements and exhaust gas aftertreatment. The U.S. Environmental Protection Agency (EPA) has adopted more stringent emission standards for NO_x, HCs, and PM from new nonroad diesel engines.[10] More recently, regulations have been issued to reduce stationary diesel emissions.[11]

Diesel backup generators (BUGs) are often located close to hospitals, schools, and municipal buildings where the potential for human exposure is high. It has been estimated that there were 626,000 installed units of diesel BUGs with a total generating capacity of 102,000 MW in the United States in 1996 and the capacity is growing at an annual rate of 1.7%.[12]

A few characterizations of BUG emissions have been reported.[13–20] Liu et al.[13] reported that the fraction of EC and OC of DPM emissions changed from 21 to 84% and 62 to 9%, respectively, for a 75-kW BUG as load increased from 0 to 75 kW. Oudejans et al.[14] measured aromatic

IMPLICATIONS

Diesel generators account for approximately 19% of all nonroad equipment fuel used by the U.S. Marine Corps. More stringent emission standards have been adopted for air pollutants such as NO_x and PM from nonroad diesel engines. This study used a portable in-plume system to characterize gaseous and particulate fuel-based EFs from military generators. Real-world EFs can be quantified by in-plume measurements and provide more realistic measures for emissions inventories, source modeling, and receptor modeling than certification measurements. These data are essential to state and local air quality planners charged with maintaining regional air quality and protecting human health.

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Table 1. Diesel BUGs tested.

Generator	Test Date	Generator Model	Hours Used	Engine Year/ Make	Serial Number	Rated Power (kW)
1	November 14, 2005	MEP803A	2618	19990nan	FZ30644	10
2	November 14, 2005	MEP803A	3103	19950nan	RZC02845	10
3	November 14, 2005	MEP803A	2154	19940nan	RZC02061	10
4[a]	November 15, 2005	MEP805A	1943	1995 JohnDeere	RZH01043	30
5	November 15, 2005	MEP805A	3374	1995 JohnDeere	RZH01023	30
6	November 15, 2005	MEP805A	1641	1995 JohnDeere	RZH00999	30
7	November 15, 2005	MEP805B	636	2002 JohnDeere	HX32455	30
8	November 15, 2005	MEP805B	85	2002 JohnDeere	HX33185	30
9	November 15, 2005	MEP806B	1017	2002 JohnDeere	HX62471	60
10	November 15, 2005	MEP806B	1084	2001 JohnDeere	HX62182	60
11	November 15, 2005	MEP806A	947	1995 JohnDeere	RZJ02059	60
12	November 15, 2005	MEP806B	366	2001 JohnDeere	HX62178	60
13	November 16, 2005	MEP007B	1874	NA	RZ02630	100
14[b]	November 16, 2005	MEP805B	29	2002 JohnDeere	HX33189	30

Notes: All are four-stroke diesel engines on the basis of military manuals. [a]Tested for five engine loads with no cold start; [b]Tested only for cold start.

emissions from a BUG using resonance-enhanced multiphoton ionization time-of-flight mass spectrometry (REMPI-TOFMS) and determined that HC and volatile organic compound emissions rates were higher (e.g., up to a factor of 90 for benzene) during cold starts (i.e., during the first 40 sec after startup) than during hot-stabilized operation. Gullet et al.[15] report that several organic air toxic (e.g., benzene and naphthalene) emissions during cold starts were 15 times those for a hot-stabilized 60-kW BUG.

Reported here are fuel-based particulate and gaseous emissions factors from 14 military diesel generators (Mobile Electrical Power) with rated capacities of 10, 30, 60, and 100 kW under different load conditions. Replicate measurements from different engines with the same model (rated capacity) of 10, 30 and 60 kW were made. On the basis of the fuel consumption reported by the U.S. Marine Corps (USMC), the 10-, 30-, and 60-kW generators account for 19.1% of total fuel consumption of USMC nonroad diesel engines.[21] Fuel usage by 100-kW generators was not reported.

EXPERIMENTAL METHODS

Test engines (Table 1) were selected to represent a range of operating hours, manufacturers, and model years. The test cycle consisted of 5 min at 100, 75, 50, 25, and 10% engine loads simulated by an electrical resistance load.[22] Cold-start emissions were measured separately during the first 5 min after ignition at 0% load after an overnight cold soak of at least 16 hr. Seventy-nine tests (13 cold starts) of engines operating at a specific mode were performed between November 14 and 16, 2005. Fuel-based emission factors (EFs; g pollutant emitted/kg fuel burned) were calculated from the ratio of the pollutant of interest to the sum of carbon dioxide (CO_2) and CO concentration (above ambient background) in the plume and the carbon content of the fuel.[23] CO and CO_2 typically account for more than 99% of the carbon emitted in engine exhaust.[24]

Gas and PM concentrations in the exhaust plume were quantified using the Desert Research Institute (DRI)'s In-Plume Emission Test Stand (IPETS). The instrumentation and operating methods are described in detail by Nussbaum et al.[25] The IPETS uses a Fourier transform infrared spectrometer (FTIR; Midac) to measure gas (CO, CO_2, nitric oxide [NO], nitrogen dioxide [NO_2], nitrous oxide [N_2O], ammonia [NH_3], sulfur dioxide [SO_2], propane, ethylene, and hexane) concentrations and an electrical low pressure impactor (ELPI; Dekati) to measure real-time particle size distributions characterizing engine PM emissions after mixing with ambient air. Two DustTrak Model 8520 light scattering monitors[26] (TSI) measured $PM_{2.5}$ and PM less than 10 μm in aerodynamic diameter (PM_{10}), and two GRIMM Model 1.108 optical particle counters[27] characterized PM in the size range of 0.3–20 μm by optical detection. A photoacoustic system[28] was used to measure EC mass concentrations in the plume. With sample air drawn through a plenum using a Bendix $PM_{2.5}$ cyclone operating at a flow rate of 113 L/min, $PM_{2.5}$ samples were collected using two filter packs in parallel: (1) a 47-mm Teflon filter (gravimetric mass) followed by quartz fiber filter (volatilized PM OC), and (2) a quartz fiber filter (water-soluble ions, OC/EC) followed by a sodium-carbonate-coated cellulose fiber filter (for SO_2) and a citric-acid-impregnated cellulose fiber filter (for NH_3). Gaseous detection limits by the Midac Illuminator FTIR are reported in Table 2. The FTIR's wavenum-

Table 2. FTIR spectrometer detection limits of gaseous species.

Species	Detection Limit (ppm)
CO_2	12
CO	0.2
NH_3	0.06
NO	1
H_2O	60
Butane	0.05
Hexane	0.2
Ethylene	0.1
NO_2	0.4
SO_2	0.5

ber scan resolution is 0.5 cm^{-1} with a sample flow of 50 L/min through a 2-L optical cell with a 10-m folded light path. The data sampling rate was 1 per 1.5 sec. The sampling line and cell were not heated and the water was not removed from the exhaust sample. For species of interest, particularly NO and NO_2, the interference due to water vapor was greatly reduced by the least-squares algorithm within Midac's Autoquant software.[25]

The sampling inlet is typically mounted approximately 1 m from the generator's exhaust pipe. The IPETS uses a direct ambient dilution method to measure pollutants from real-world dilution conditions. CO_2 is used as a tracer for the exhaust plume. With a stoichiometric amount of air, the CO_2 concentration in raw gasoline exhaust is approximately 12.4%, or 124,000 parts per million (ppm).[29] Diesel engines always operate with an excess of air, and the CO_2 concentrations in diesel exhaust range between approximately 2 and 3% at low power and 10% at high power.[30] Bergmann et al.[31] also found a CO_2 concentration range of approximately 1–11% in undiluted exhaust from a diesel car. The average CO_2 concentration from testing cycles ranges from 600 to 4500 ppm, which means the approximate ambient dilution ratio in this study ranged from 22 to 40. On the basis of the flow rate of the system (~200 L/min), and an approximately 4.7 m long (2.54 cm inner diameter [ID]) plus 1 m long (1.27 cm ID) sampling line before the exhaust goes into the ELPI, the residence time of exhaust in the sampling line is approximately 1.3 sec.

The background measurement for FTIR gas species was sampled 3 times in a day; that is, beginning, middle, and end of sampling day. Background CO_2 and $PM_{2.5}$ concentrations in ambient air were also quantified with a LI-COR LI-840 H_2O/CO_2 monitor and a $PM_{2.5}$ filter sampler located approximately 20 m from the test engine to subtract the effects of outdoor air mixed with the slightly diluted plume. Ambient temperature and relative humidity (RH) were monitored and recorded every hour. Average and standard deviations of ambient temperature and RH during the sampling period were 28.5 ± 4.5 °C and 25.8 ± 10.1%, respectively. Figure 1 shows an example from five load cycles.

A few fuel samples drawn from the supply jerry cans and the fuel tanks of the 60- and 100-kW generators with compositions are shown in Table 3. Samples from the jerry cans were consistent with California no. 2 diesel specification,[32] having sulfur contents of 139 and 148 parts per million by weight (ppmw), respectively; whereas the 60- and 100-kW generator tank samples were consistent with the JP-8 criteria,[33] with sulfur contents of 311 and 349 ppmw, respectively. At the time of sampling, the military base was temporarily unable to obtain JP-8 fuel for the generator sets and were using California no. 2 diesel to refuel the generators when needed. On the basis of these facts, except for the 60-kW HX62178 and 100-kW RZ02630, the authors were unable to confirm the exact type or relative blend of fuels (JP-8 or California no. 2 diesel) used in the generators.

EF Calculation

The fuel-based EF_i with units of g pollutant *i* emitted per kg fuel burned is[23]

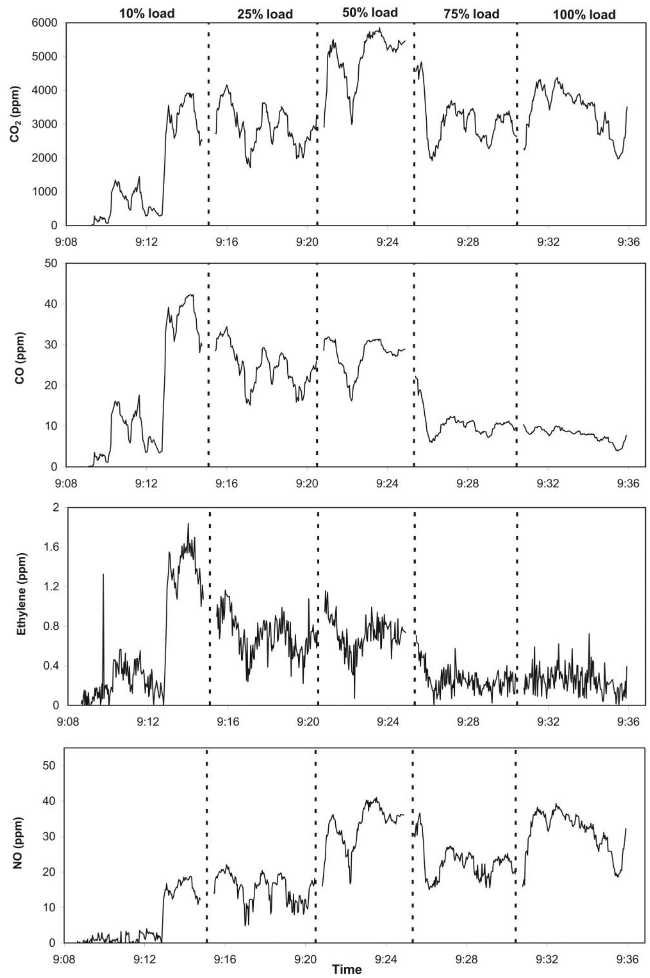


Figure 1. Background-corrected (a) CO_2, (b) CO, (c) ethylene, and (d) NO under five operating loads for a 30-kW generator on November 15, 2005. The changes within each cycle are due to different levels of plume dilution, as indicated and compensated for by the fluctuating CO_2 levels.

$$EF_i = CMF_{diesel}\frac{\dfrac{\rho_i}{\rho_{CO_2}}}{CMF_{CO_2} + CMF_{CO}\dfrac{\rho_{CO}}{\rho_{CO_2}} + \left(CMF_{HC}\dfrac{\rho_{HC}}{\rho_{CO_2}}\right)}, \tag{1}$$

where ρ_i, ρ_{CO2}, ρ_{CO}, and ρ_{HC} are the excess (above ambient) concentrations ($\mu g/m^3$) of pollutant *i*, CO_2, CO, and HC, respectively; and *CMF* is the carbon mass fraction of each pollutant with CMF_{CO} = 42.9%, CMF_{CO2} = 27.3%, and CMF_{diesel} = 86.6% (assuming $CH_{1.85}$ for diesel fuel). For most engines, the term in parentheses in eq 1 can be neglected because HC accounts for less than 0.5% of carbon emissions. As shown in Figure 2, excess NO is highly correlated (R^2 = 0.98) with the sum of the excess CO and CO_2 in the exhaust plume. Mode-independent (weighted) EFs for a specific engine are calculated using weighting factors of 0.10, 0.30, 0.30, 0.25, and 0.05 for the 10, 25, 50, 75, and 100% loads, respectively.

Table 3. Properties of military diesel fuels standard analysis (Intertek Caleb Brett Laboratories in Deer Park, TX).[32]

Method	Test	Units	November 14, 2005 Sampled from Refueling Jerrycan 2005-7152-DRPK-001	November 15, 2005 Sampled from Refueling Jerrycan 2005-7152-DRPK-002	November 16, 2005 Sampled from 60-kW, HX62178 2005-7152-DRPK-003	November 16, 2005 Sampled from 100-kW, RZ02630 2005-7152-DRPK-004	JP-8 Spec (MIL-DTL-831333E)	California Diesel Fuel Registration (CCR Title 13, Division 3,Ch. 5, Art. 2)
ASTM D2500	Cloud point	ºC	−11	−12	−56	−56		
	Cloud point	ºF	12.2	10.4	−68.8	−68.8		
ASTM D2622	Sulfur	ppm (wt)	148	139	311	349	*<3000*	**<500**
ASTM D2709	Sediment and water	vol %	0	0	0	0		
ASTM D4052 (IP 365)	API gravity 15.56 °C, 60 °F	ºAPI	35.0	35.3	41.0	41.2	*37 <x<51*	**33<x <39**
ASTM D86	Initial boiling point	ºF	372.5	366.1	392.2	**312.5**		**340<x<420**
	5% Recovery	ºF	415.0	407.4	358.4	353.7		
	10% Recovery	ºF	*433.4*	*427.6*	**362.0**	**355.2**	*<401*	**400<x<490**
	20% Recovery	ºF	467.3	455.7	376.8	370.5		
	30% Recovery	ºF	495.5	484.3	386.8	382.3		
	40% Recovery	ºF	523.8	514.3	398.6	393.6		
	50% Recovery	ºF	549.7	541.4	**410.4**	**405.3**		**470<x<560**
	60% Recovery	ºF	573.5	568.4	421.9	417.7		
	70% Recovery	ºF	596.9	592.9	436.5	432.1		
	80% Recovery	ºF	617.8	614.2	454.4	449.1		
	90% Recovery	ºF	**638.0**	**635.5**	**483.1**	**475.1**		**550<x<610**
	95% Recovery	ºF	654.4	655.5	513.6	498.3		
	Final boiling point	ºF	*658.1*	*663.7*	**546.4**	**530.4**	*<572*	**580<x<660**
	% Recovered	vol %	96.6	97.8	97.7	98.5		
	% Residue	vol %	*1.9*	1.1	*2.0*	1.4	*<1.5*	
	% Loss	vol %	1.5	1.1	0.3	0.1	*<1.5*	
ASTM D93 (IP 34)	Corrected flash point	ºC	96.5	**52**	**51**	71	*>38*	**>55**
Method A	Corrected flash point	ºF	205.5	**125.5**	**123.5**	159.5	*>100*	**>130**
ASTM D976 (IP 364)	Calculated cetane index	51.1	50.9	**40.6**	**39.8**	**>48**		

Notes: Values outside of the military JP-8 specifications[33] are shown in *italics* and values outside of the California no. 2 diesel specification are shown in **bold**.

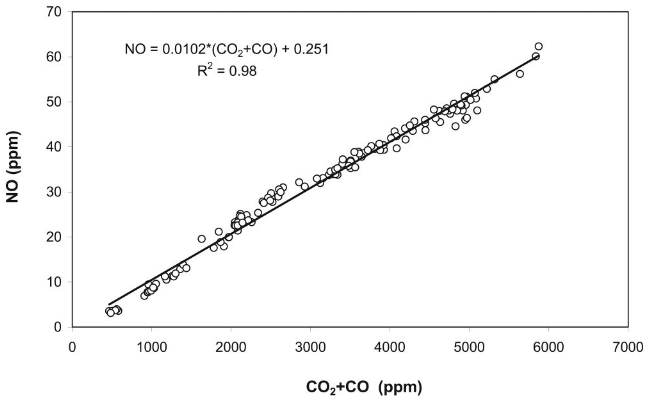


Figure 2. Correlation of NO with CO + CO_2 concentration over a 100% load cycle of 30-kW generator RZH01023 test on November 15, 2005.

ELPI Particle Mass Concentration

The ELPI passes incoming particles by a corona charger and measures the current dissipated from cascade impactor stages, onto which the particles are collected for the size range from 7 nm to 10 μm with the filter stage. The charging efficiency of each particle depends on its mobility diameter, d_m, whereas the ELPI sizes particles on the basis of their aerodynamic diameter, d_a. The effective particle density, ρ_e, establishes the relationship between d_m and d_a as[34]

$$\rho_e C_c(d_m) d_m{}^2 = \rho_0 C_c(d_a) d_a{}^2, \tag{2}$$

where C_c is the Cunningham correction coefficient.

DPM size distributions are approximated by three lognormal modes: nuclei (3–30 nm), accumulation (30–500 nm), and coarse (>500 nm). Approximately 80–90% of DPM mass is found in the range of the accumulation mode.[35] ELPI as a measurement of number size distribution is in good agreement with other instruments such as the scanning mobility particle sizer (SMPS).[36] The standard data reduction software for ELPI converts the measured current on each stage into a PM mass concentration by assuming that the particles have unit density, are spheres, and $d_m = d_a$. In fact, DPM particles are fractal-like agglomerates of approximately spherical 10- to 30-nm primary particles. Maricq et al.[37] and Park et al.[38] found that the DPM effective mass density decreases with particle size.

The GRIMM optical counter measurements indicated that only a small concentration of particles larger than 500 nm was in the military generator exhaust, whereas the ELPI measured a large coarse mode (Figure 3). Maricq et al.[39] have shown some charge-bearing nanoparticle diffusional deposition on the upper (i.e., large particle) stages of the impactor, thereby creating additional current on the upper stages of the impactor not associated with coarse particles. Virtanen et al.[40] reported that the diffusion loss of fine particles onto upper stages of ELPI is less than 6%. The fine particle losses to the upper stages are not critical for mass measurement because the real mass introduced by fine particles is insignificant. Maricq et al.[39] reported that ELPI standard data reduction overestimates the PM mass by as much as 115% compared

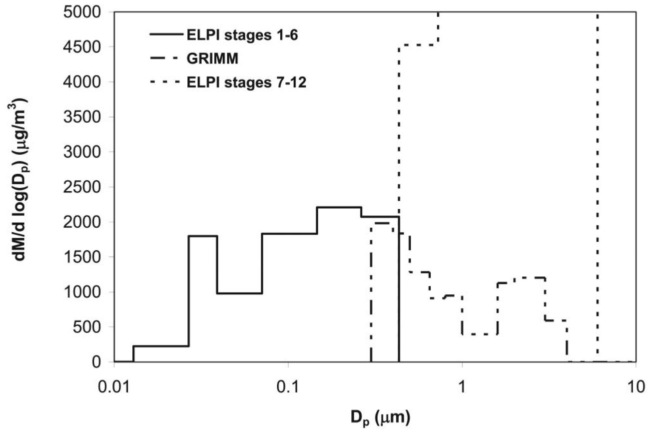


Figure 3. Composite size distribution of DPM measured by the ELPI and the GRIMM optical particle counters. The dashed line represents a large particle artifact for the ELPI measurement.

with gravimetric filter mass for diesel exhaust and devised a least-squares fitting algorithm to account for changes in density and the coarse artifact. This algorithm solves the mean diameter, μ_g, and number concentrations, N_0, for nuclei and accumulation modes that best describe the ELPI currents. Following Maricq et al.,[39] accumulation mode particles were assumed to have a geometric standard deviation (GSD) σ_{ac} of 1.7 and a fractal dimension, d_f, of 2.3. The nuclei mode particles were assumed to be spherical, have a GSD σ_{nuc} of 1.2 with unit density, and a d_f of 3. The PM mass, M, is

$$\begin{aligned} M = {} & N_{nuc}\frac{\pi}{6}\rho_{nuc}u_{nuc}^3 e^{9(\ln\sigma_{nuc})^2/2} \\ & + N_{ac}\frac{\pi}{6}\rho_0 d_0^{(3-d_f)}\mu_{ac}^{d_f} e^{d_f^2(\ln\sigma_{ac})^2/2} \end{aligned} \tag{3}$$

where the ρ_0 is the primary particle density of 2 g/cm^3,[41] and d_0 is the primary particle diameter of 20 nm. PM mass values from eq 3 were compared with those from the standard ELPI reduction algorithm for stages 1–6 (D_{50} = 322 nm) and the $PM_{2.5}$ mass concentrations measured on Teflon filters are shown in Figure 4. Filter samples integrated results from a full test cycle or multiple engines in the case of cold starts. On average, the ELPI-simulated PM mass was 19% higher than the filter measurements, whereas the ELPI standard PM mass was 99% higher on average than filter PM mass. Maricq et al.[39] found similar comparisons with PM mass collected on filters. The limitation of ELPI for PM mass measurement has been greatly improved via the correction algorithm. On the basis of gravimetric filter measurements, PM concentrations in the exhaust plumes were at least 2 orders of magnitude higher than the ambient background, precluding the need to subtract background PM concentrations during the engine tests. The IPETS fuel-based PM EFs were calculated when valid measurements were available for CO, CO_2, and ELPI. PM EFs were calculated using the average background-subtracted gas concentrations measured by the FTIR and bimodal fitting ELPI PM. The intercomparison of the light scattering (DustTrak), impaction (ELPI),

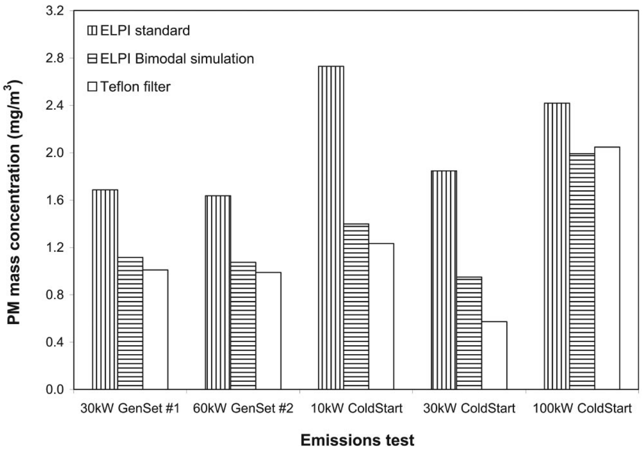


Figure 4. Comparison of PM from different generator tests by the standard ELPI data reduction, the ELPI bimodal fitting procedure, and gravimetric mass on Teflon filters.

and gravimetric (filter) method was detailed in the first paper of the IPETS system by Nussbaum et al.[25] Of the real-time instruments, because of the fractal-like agglomerate character of diesel soot and most particles less than 500 nm, the 780-nm wavelength of DustTrak and the Grimm minimum sampling size of 300 nm limit their capability to better characterize DPM. The ELPI-simulated PM mass concentration has the best agreement with gravimetric filter PM mass concentration. Except for the PM source profile analysis, the PM reported in this paper results from the corrected ELPI PM.

RESULTS AND DISCUSSION

Replicate Measurements

To evaluate the uncertainty of IPETS measurements, replicate tests for a 2000 model-year 250-kW Komatsu diesel generator running with JP-8 were conducted. The coefficient of variation (COV) obtained for these tests are summarized in Table 4.

Gaseous EFs

Average EFs for each engine type are summarized in Figures 5 and 6. CO, ethylene, and NO_2 EFs decreased with increasing engine load. Cold-start EFs (measured during the first 5 min of operation after an overnight cold soak) were higher than the hot-stabilized (i.e., running for at

Table 4. IPETS replicate measurements on a 250-kW Komatsu diesel generator running with JP-8.

NO_x EF (g/kg fuel)	Filter $PM_{2.5}$ EF (g/kg fuel)
29.34	0.39
28.55	0.4
0.56	0.01
28.95	0.4
1.90%	2.20%

Notes: The COV between replica tests is much less than the interengine EFs variation observed with the military generators in this study.

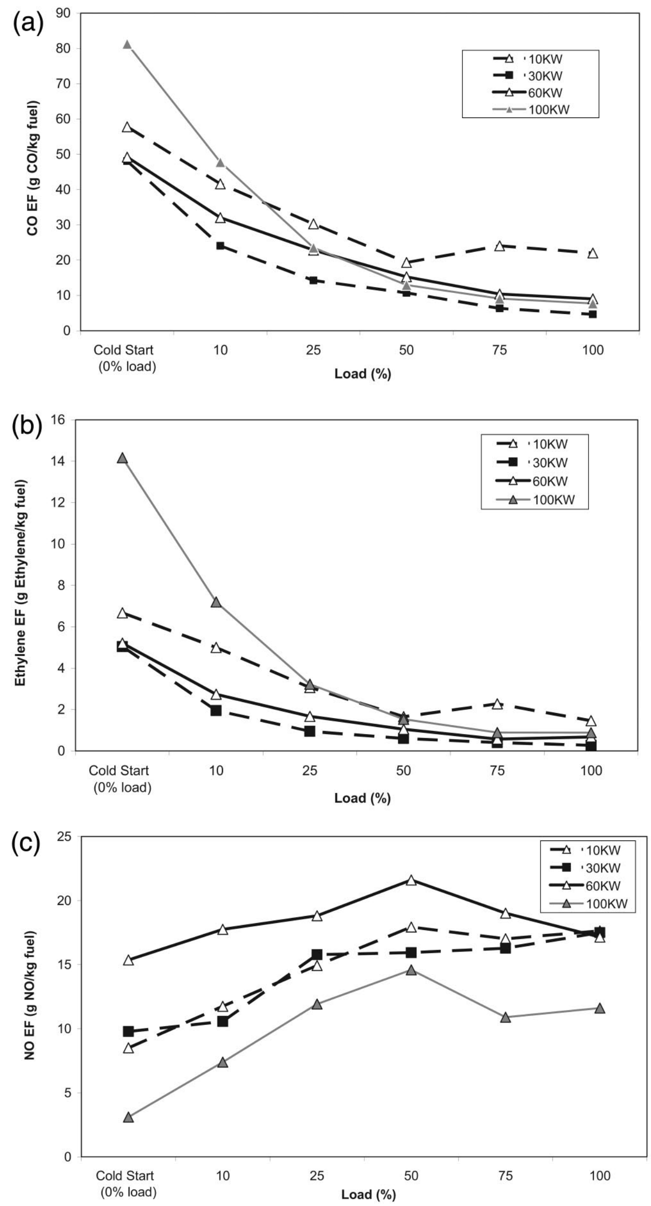
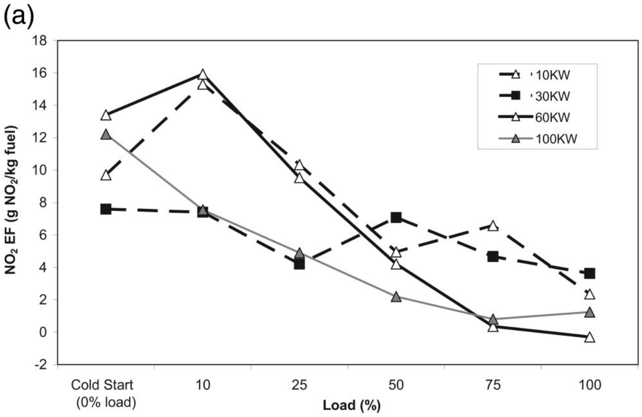


Figure 5. Average (a) CO, (b) ethylene, and (c) NO EFs for all engines tested.

least 20 min before measurement), steady-state, loaded modes. Ethylene EFs are consistent with the emission of unburned fuel during the initial fuel-rich combustion.[42] As the engine cylinders heat up at higher load, the combustion efficiency improves, and less CO is produced.

NO (the primary constituent of NO_x in exhaust) EFs are shown in Figure 5c. At 10% load, the air-to-fuel ratio is highest, leading to low combustion temperatures and lower NO emissions. During cold start (no load conditions), NO EFs were less than corresponding hot-stabilized NO EFs at each generator power rating. With the exception of 30-kW generators, all NO EFs were highest at 50% load and then decreased above 75% load. When the engine load approached 100%, the NO EFs increased slightly compared with the 75% load for all but the 60-kW generators. NO EF changes with engine load are consistent with higher fuel-to-air ratio at 100% load.[43] These



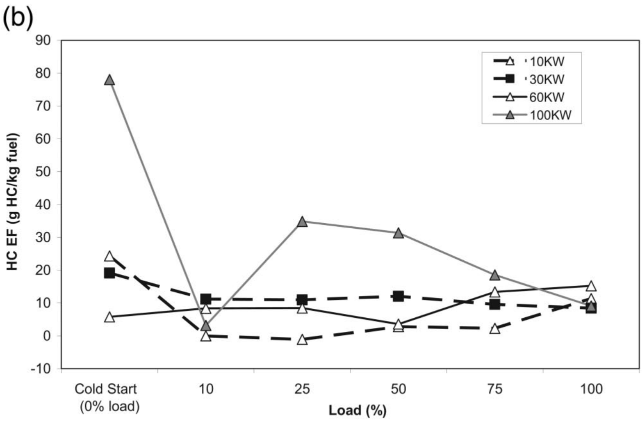


Figure 6. Average (a) NO_2 and (b) HC EFs for all engines tested.

changes of NO EFs with load were also observed by Cocker et al.[16] on a 350-kW BUG.

HC EFs (sum of ethylene, propane, and hexane) were less than 20 g HC/kg fuel. HC emissions increased with engine load for 10- and 60-kW engines, but they decreased with load for 30- and 100-kW engines. Except for the 60-kW generators, the average cold-start HC EFs were approximately 7 times higher than the weighted HC EFs at hot-stabilized modes. This is consistent with the presence of unburned fuel during the initial fuel-rich combustion. NH_3 EFs were less than 0.2 g NH_3/kg fuel and were often below the detection limits.

Comparison with Previous Generator Emission Studies

Cocker et al.[16] measured emissions from of a 350-kW BUG equipped with a CAT 3406C engine (model year 2000) using a mobile emission laboratory (MEL). Shah et al.[18] compared emissions from 18 BUGs ranging in rated capacity from 60 to 2000 kW and reported the regulated pollutant EFs calculated on the basis of power output of the engine in units of g/kWh. Following the convention of EPA regulations and the MEL reporting, NO_x EFs are reported as $1.53 \times$ NO EF + $1 \times NO_2$ EF such that NO_x EFs have units equivalent to g NO_2/kg fuel.

EPA's AP-42[44] EFs for small diesel-fueled internal combustion engines (<440 kW) are based on energy output (i.e., units of g pollutants/kWh) and have been converted into fuel-based EFs (by converting kWh into kg fuel) for comparison with the results presented here. An average brake-specific fuel consumption (BSFC) of 9899 kJ/kWh (corresponding to an efficiency of 36.4%) and a diesel heating value of 44,889 kJ/kg[44] yields a conversion factor of 4.53 kWh/kg fuel, which is multiplied by EPA's energy-based EFs to obtain fuel-based EFs in units of g pollutants/kg fuel. The conversion yields EPA AP-42 EFs for diesel engines less than 440 kW of 85 g NO_x/kg fuel, 18 g CO/kg fuel, 5.6 g SO_x/kg fuel, 6 g PM/kg fuel, 1.4 g aldehydes/kg fuel, and 6.8 g total OC (TOC)/kg fuel.

Table 5. Fleet average EFs for NO_x, CO, and PM for tested generators.

	NO_x (g/kg fuel)	CO (g/kg fuel)	PM (g/kg fuel)
Average	31	17	1.2
Standard deviation	8.4	7.3	0.6
COV	27%	42%	51%
AP-42 EF	85	18	6

Average EFs and standard deviations for the generators tested are presented in Table 5. The average CO EF (17 g/kg fuel) of generators tested in this study was comparable to the AP-42 EF of 18 g CO/kg fuel, whereas NO_x and PM EFs were much lower than AP-42 EFs.

Of the 18 diesel BUGs that Shah et al.[18] tested with their MEL, only 3 generators had similar power ratings to the generators tested here, and their EFs are compared with IPETS results in Table 6. The CO EFs of Shah et al.[18] were approximately 47% lower than AP-42 EFs. For these three BUGs, the 2001 model-year 60-kW (58 operating hours) and 1990 model-year 100-kW (419 operating hours) engine's NO_x EFs were higher at low load, decreased at mid-loads, and were highest at 100% loads. NO_x EFs for the 125-kW (270 operating hours) engine were highest at low load and decreased with increasing load similar to the IPETS' NO_x EFs for the four 60-kW engines. For the 100-kW engine tested with IPETS, the NO_x EFs peaked at 50% load, with a minimum at 75% load and a slight increase at 100% load. The 10-, 30-, and 60-kW generator group average NO_x EF is 32.7, 29.3, and 35.7 g/kg, respectively. Of the 14 generators tested in this study, NO_x EFs depended on engine type and load. Newer model-year generator NO_x EFs did not differ from older models, which might be because even for newer model years, most nonroad diesel engines under 50 hp (38 kW) tend to be indirect injection.[45]

Particulate EFs

Fuel sulfur content in diesel and JP-8 has not shown a consistent effect on emissions from prior studies. Saiyasitpanich et al.[46] found PM emissions from an 80-kW generator operating at 75-kW load increased by nearly a factor of 2 (6.9 to 12.60 g PM/hr) when fuel sulfur content increased from 500 to 2100 ppmw. Durbin et al.[47] reported that 461-ppmw sulfur JP-8 produced 4% more NO_x and 35% more PM mass emissions compared with 2-ppmw ultralow sulfur diesel (ULSD) for a 2004 Humvee.

Table 6. IPETS EFs from this study compared with previously reported results from a MEL.[18]

Instrument/Engine Type and Model Year	Pollutant	Percent Load 10	25	50	75	100	Weighted[a]	AP-42[b]
IPETS EF 60-kW Average (1995, 2001, 2001, 2002)	THC	5.6	6.8	2.5	13	15	7.3	6.8
	CO	32	23	15	10	9	18	18
	NO_x	43	38	37	29	26	36	85
	PM	1.1	1.2	1.9	2.6	2.1	1.8	60
IPETS 100 kW (LIBBY MEP007B, year unknown)	THC	12	-0.3^{c}	5.2	30	22	11	–
	CO	47	24	13	8.1	6.9	18	–
	NO_x	19	23	25	18	19	22	–
	PM					0.5		–
MEL EF 60-kW John Deere (2001)	THC	33	12	5.2	3.2	2.1	9.3	–
	CO	36	13	4.6	2.4	6.3	9.7	–
	NO_x	50	32	35	44	55	39	–
	PM	2	1.6	1.0	1.0	1.8	1.3	–
MEL 100-kW Cummins 6BT, 1990	THC	31	16	6.6	4.1	1.9	11	–
	CO	32	14	3.5	5.0	26	11	–
	NO_x	54	49	48	68	79	55	–
	PM	3.0	2.3	0.8	0.6	1.5	1.5	–
MEL 125-kW John Deere 6076, 1991	THC	26	9.3	5.0	3.5	3.0	7.9	–
	CO	30	8.6	4.2	3.8	6.0	8.1	–
	NO_x	150	89	77	74	74	87	–
	PM	4.0	1.5	0.8	0.7	0.8	1.3	–

Notes: Values presented in g pollutant/kg fuel. [a]Weighting factors of 0.1, 0.3, 0.3, 0.25, and 0.05 for the 10, 25, 50, 75, and 100% loads respectively; [b]AP-42 EFs for uncontrolled diesel industrial engines; [c]The THC EF is below the detection limit of the FTIR instrument.

For a 60-kW generator in the same study, PM emissions using JP-8 were 50% less than those for ULSD. For a 250-kW generator, PM emissions using JP-8 were 14% higher than those for ULSD and NO_x emissions changed less than 15% between these two fuels for the two generators. The IPETS was collocated with the MEL used by Durbin et al.[47] for the 250-kW generator tests, described by Nussbaum et al.[25]; the IPETS $PM_{2.5}$ EFs were approximately 3% lower for JP-8 compared with ULSD, and the IPETS NO_x EFs were approximately 13% higher for JP-8 compared with ULSD, well within the range of interengine PM and NO_x EFs observed with the military generators reported in this study. In contrast, Yost et al.[48] found that PM emissions decreased by 22% with 600-ppmw sulfur JP-8 versus 350-ppmw sulfur EPA certification fuel. CO, NO_x, and HC emissions were the same for both fuels in that study. Frame and Blanks[49] found that a 6.5-L HMMWV engine using 87.3-ppmw sulfur JP-8 produced 11% less NO_x and 28% less PM emissions than with 37-ppmw low-sulfur certification diesel; the difference in BSFC between JP-8 and certification diesel in this 6.5-L engine was 8%. Kouremenos et al.[50] found that NO_x, CO, HC, and PM emission rates were the same within experimental error for the 3000-ppmw sulfur no.2 diesel and 1500-ppmw sulfur JP-8 in a four-stroke diesel engine. The lack of consistency from these studies suggests that the influence of fuel type (i.e., JP-8 vs. no. 2 diesel) on EFs is likely to be less than 30% when fuel sulfur contents are below 500 ppmw.

Figures 7 and 8 summarize PM EFs using an ELPI PM correction algorithm. The 60-kW generator group average PM EF (1.8 ± 0.4 g PM/kg fuel) is more than twice as large as the 30-kW generator group average (0.77 ± 0.19 g PM/kg fuel). The fleet average (30 and 60 kW) PM EF was 1.2 ± 0.6 g PM/kg fuel, one-fifth of the corresponding AP-42 value of 6 g PM/kg fuel. PM EFs measured by MEL were also 83% lower than the AP-42 values for small engines (<441 kW). Some of these discrepancies may be due to Method 5 used to measure the AP-42 PM. For EFs that included filterable and condensable PM, the Method 5 results in a mass loading that is up to three times higher than the filter-based method.[18,51]

All engines showed an increase in PM EFs as the load increased to 75 or 100% of the maximum rating (Figure 8). Only one valid PM EF is reported for the 100-kW engine at 100% load because the current measured on one or more of the ELPI impactor stages exceeded the analytical limit on the remainder to the operating mode tests.

For the 30- and 60-kW generators, cold-start PM EFs were 46 and 89% higher than the PM EFs at 10% load conditions, consistent with fuel-rich combustion conditions during a cold start. The average IPETS PM EF of four 60-kW BUGs (1.8 g/kg fuel) was 38% higher than MEL PM EFs of the 60-kW BUG (1.3 g/kg fuel) measured by filter sampling of the diluted exhaust. In addition to the variation of emissions between engine models, some of this difference may be associated with the MEL DPM sampling temperature. Cocker et al.[16] reported a test with the MEL filter face temperature set at 27 °C versus the standard heated temperature of 47 °C. The high-temperature tests recovered approximately 11% less PM mass than the test at 27 °C. The IPETS system operates near ambient temperatures and may permit more semi-volatile components to condense onto PM and onto filters before and during collection.[52]

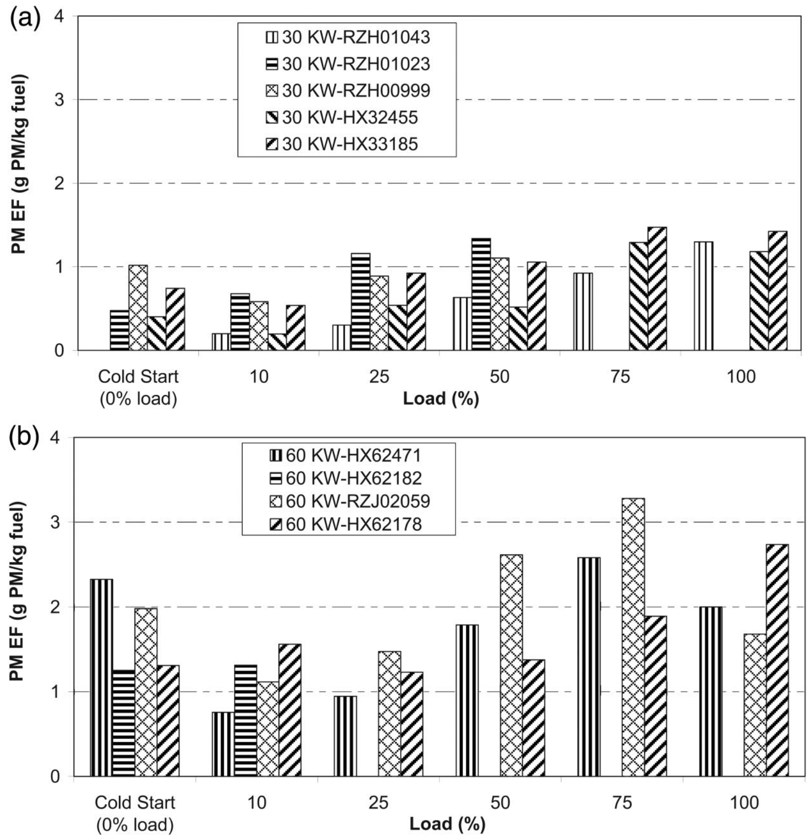


Figure 7. PM fuel-based EFs for (a) 30- and (b) 60-kW generators tested between November 14 and 16, 2005. Because of insufficient dilution, if the 25% of current data recorded by ELPI exceeded the 400,000-fA instrument limit, the PM data were invalid for that cycle.

For 60-kW engines, the 2002 John Deere generator did show a 25% PM EF reduction compared with the 1995 John Deere, which may reflect the engine changes to meet more stringent 2004 emission standards. For 30-kW engines, such PM reduction was not observed between 1995 and 2002 models, possibly because of the preferred indirect injection used in the small-capacity engine group.[45]

DPM Source Profiles and EC/OC

Filter samples were analyzed by gravimetry, ion chromatography, X-ray fluorescence, colorimetry, and thermal/optical reflectance (TOR).[53,54] Source profiles of the relative abundance of chemical species collected on the filter were calculated from the sum of particles species measured above the ambient background. Most exhaust $PM_{2.5}$ mass is composed of total carbon (TC), which equals the sum of OC and EC, with EC accounting for 9–47% of the $PM_{2.5}$ mass. TC accounts for between 94 and 98% of $PM_{2.5}$ mass under various start conditions. On average, OC accounts for 65 and 82% and EC accounts for 31 and 16% for hot-stabilized and cold-start conditions, respectively.

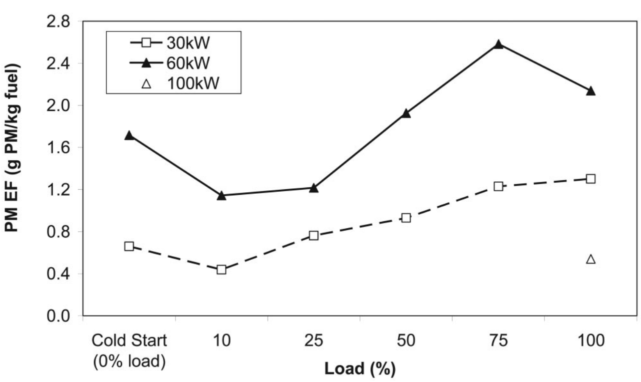


Figure 8. Average PM EFs as function of load for three generator load ratings. For the 100-kW generator, only the 100% load has valid ELPI data with <25% of current data exceeding the instrument limit.

$PM_{2.5}$ mass fraction values were reported for water-soluble ions and gaseous SO_2 and NH_3. $PM_{2.5}$ sulfate (SO_4^{2-}) values were low and variable, averaging 1.3 ± 1.1% of $PM_{2.5}$ mass for hot-stabilized operation and 0.5 ± 0.5% of $PM_{2.5}$ mass for cold starts. Higher SO_2 (41 ± 37% of $PM_{2.5}$ mass) was reported for cold starts than hot-stabilized operation (24 ± 19%). $PM_{2.5}$ SO_4^{2-} and SO_2 levels were also lower than the 2.4 ± 1% and 67 ± 24% of $PM_{2.5}$ mass reported by Watson et al.[55] This reflects the reduction of sulfur content in diesel fuel over the past 2 decades. $PM_{2.5}$ ammonium was low, averaging 0.6 ± 0.4% of $PM_{2.5}$ mass for hot-stabilized operation and 0.3 ± 0.3% for cold starts. Low levels of NH_3 were detected, with 0.05 ± 0.05% of $PM_{2.5}$ mass for hot-stabilized operation and 0.3 ± 0.6% for cold starts. Other water-soluble ions such as chloride, nitrate, sodium, and potassium were low (typically <0.05% of $PM_{2.5}$ mass).

On average, the OC/EC mass ratio for hot-stabilized engine operation (3.98) was approximately 40% less

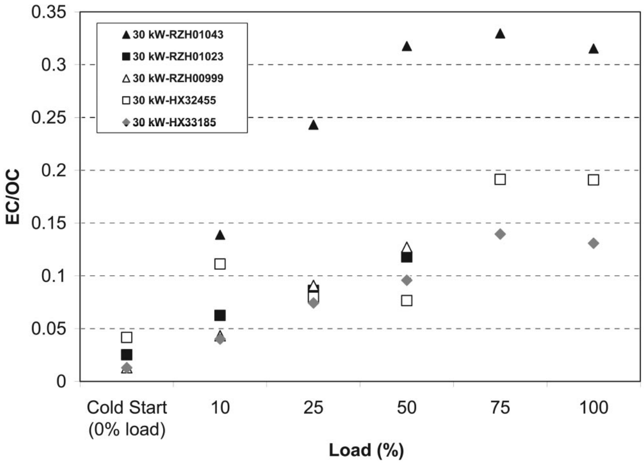


Figure 9. EC/OC ratios for PM emissions from five 30-kW diesel generators.

than that for cold starts (5.60). Approximately 69% of EC mass reported in this study was present in the high-temperature EC2 fraction (740 °C at 98% He/2% oxygen [O_2] atmosphere), with 0.3–15% of EC mass in the EC3 fraction (840 °C at 98% He/2% O_2 atmosphere). On average, $PM_{2.5}$ OC accounted for 48–89% of $PM_{2.5}$ mass, with 31–40% of OC mass found in the low-temperature OC1 (140 °C at 100% He atmosphere) and 45% of OC mass found in the OC2 fraction (280 °C at 100% He atmosphere) during hot-stabilized engine operation—twice those found during cold starts (23%). During TOR analysis, the thermal OC fraction abundances decreased with increasing temperature (i.e., OC fraction 1 concentration through OC fraction 4 concentration), indicating that the OC is quite volatile.

To estimate the EC/OC ratio change at different load conditions, it was assumed that PM mass measured by ELPI provides a real-time TC concentration. Real-time EC mass was approximated by the photoacoustic instrument using a mass absorption efficiency of 5 m^2/g.[56] The cycle-averaged OC concentration ($\mu g/m^3$) was calculated by subtracting the EC from the PM mean values of each 5-min load test, similar to the procedure used by Moosmüller et al.[57] The ratio of EC mass concentration measured by the photoacoustic instrument to the total aerosol mass concentration can change as a function of engine, operating load, and air fuel mixture.[58] The EC EF increased with engine load for all generator models. As seen in Figure 9, the EC/OC ratios of 30-kW units increased with load, indicating more OC results from the incomplete combustion at lower loads. The generator RZH01043 had the largest EC/OC ratio by a factor of 2, which may be due to different engine maintenance. The EC/OC ratio can vary between 0.16 to 4.3 according to engine type, wear, and operating conditions.[59] Cold-start EC/OC ratios were less than hot-stabilized operations, consistent with that of fuel-rich, incomplete combustion at cold start.

CONCLUSIONS

Fourteen diesel generators ranging from 10 to 100 kW from a U.S. military base were tested with the IPETS to measure fuel-based gaseous and PM EFs. Gaseous EFs were consistent across engine types. EFs of CO, ethylene, and NO_2 decreased with increasing engine load, and cold-start emissions of these species were higher than hot-stabilized operation emissions. Emissions of NO increased with engine load up to mid-loads and a slight decrease with load at high loads. Cold-start NO EFs were 14–56% lower than hot-stabilized EFs. HC EFs (sum of ethylene, propane, and hexane) were generally small (<20 g HC/kg fuel) and decreased at higher load for 30- and 100-kW engines, whereas NH_3 emissions were below the detection limit. The average CO EF of the 14 generators tested was 5% lower than EPA AP-42, and the average NO_x EF was 63% lower than the AP-42 value. Bimodal fitting procedures were used to convert ELPI currents into PM mass and showed agreement within 20% of gravimetric mass measurements. The tested generators' average PM EF was 1.2 g/kg fuel, 80% less than the AP-42 estimates. The 30- and 60-kW generator engines showed an increase in PM EF as load increased from 10 to 75%. PM EF increased 46–89% for the cold-start tests as compared with the 10% load of the hot-stabilized operation on 30- and 60-kW engines. The 10-, 30-, and 60-kW group average NO_x EFs differ within approximately 20%, and the 60-kW group average PM EF is more than twice than EF of 30-kW group. EFs measured during this study were comparable with those obtained by the MEL of the College of Engineering Center for Environmental Research and Technology of the University of California–Riverside for similar engine sizes.

Filter sample analyses indicate the TC/PM mass ratio ranged from 94 to 98%, OC/PM mass ratios ranged from 48 to 89%, and the EC/PM mass ratios ranged from 9 to 47% under various operating conditions for all tested diesel generators. The EC/OC ratio generally increased with engine load.

For the same-size engines, measured EF COVs were 27% for NO_x, 42% for CO, and 51% for PM. For the 60-kW generator, the 2002 model-year engine produced 25% less PM emissions than a 1995 model, which may reflect engine changes to meet 2004 Tier 2 nonroad regulations. The change of PM and NO_x EFs between different diesel generators indicates that diesel generators EFs are dependent on engine size, engine load, unit age, and running hours. As such, averages of multiple generator EFs are needed to accurately represent emissions from a larger fleet for the purposes of emission inventories. Real-world EFs can be quantified by in-plume measurements and provide more realistic measures for emissions inventories, source modeling, and receptor modeling than certification measurements.

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